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Update on:

Improved Properties of Nanocomposites for Flywheel Applications

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ESS ENERGY STORAGE SYSTEMS

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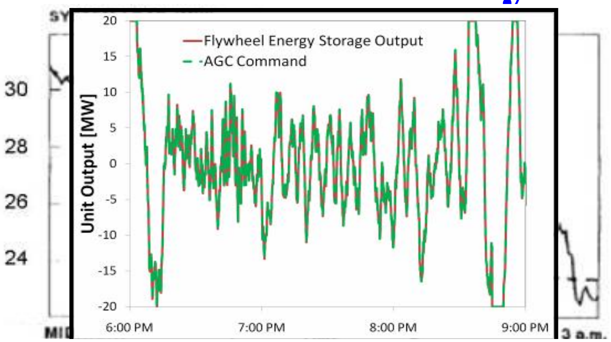
Improved materials required for next generation of flywheels to meet future needs.



A 20 MW flywheel energy storage resource accurately following a signal

Problem:

• Small changes in the AC grid necessitates rapid and exact changes for energy leveling.

• problem exacerbated upon introduction of alternative energies (i.e., solar, wind, etc.).

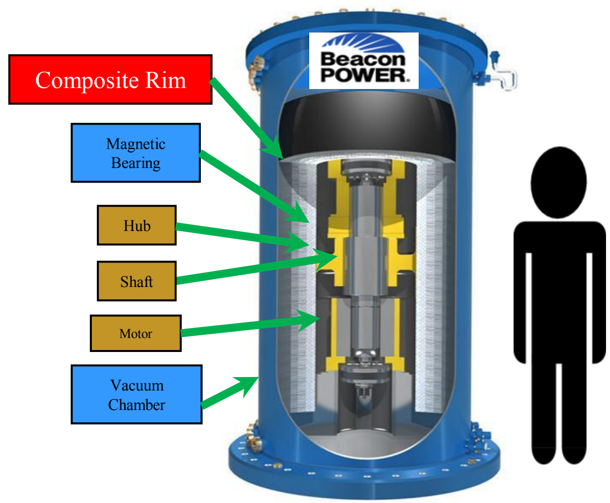
Flywheels:

• clean, rapid, and efficient method for energy leveling.

• 8 - 16,000 rpm (Mach 2) = 25 kWh

• rugged, reliable complex instruments:

rim composed of 3 components: **carbon, glass, glue (resin)**



Approach:

• obtain more extractable energy by spinning flywheels faster

• to meet the new demands, improved materials necessary

• weak link studied in this project:

- Rim : transverse failure or ‘hula-hooping’ noted
- focused on using nanocomposite materials

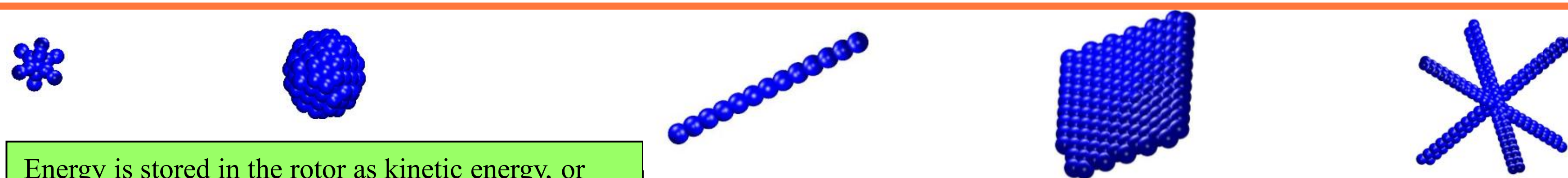
$/kWh

All flywheels have similar issues – the ‘need for speed’ - kills!

Goal: to explore nanocomposites as the rim material to improve flywheel performance.

Low load levels of nanoparticle fillers have led to dramatic property changes

Loading (wt %):	4	$Al_2Si_2O_5(OH)_4$:	*23% storage, 113% flexural strength,*[1]
	3	Al_2O_3:	*75% tensile strength,*[2]
	2	SiO_2:	*3% hardness, 57% impact, 65% flex, 88%, tensile strength,*[3]
	2	ZrP:	*52% Youngs Modulus, 14% tensile strength, 6% fracture toughness,*[4]
	0.4% CNT-2%	ZrP:	*41% Youngs Modulus, 55% tensile strength.*[5]



Energy is stored in the rotor as kinetic energy, or more specifically, rotational energy:

$$E_k = \tfrac{1}{2} \bullet I \bullet \omega^2$$

ω = angular velocity, I = moment of inertia of the mass about the center of rotation

The amount of energy that can be stored is dependent on:

$$s_t = \rho \cdot r^2 \cdot \omega^2$$

s_t = tensile stress on the rim, ρ = density, r is the radius, ω is the angular velocity of the cylinder.

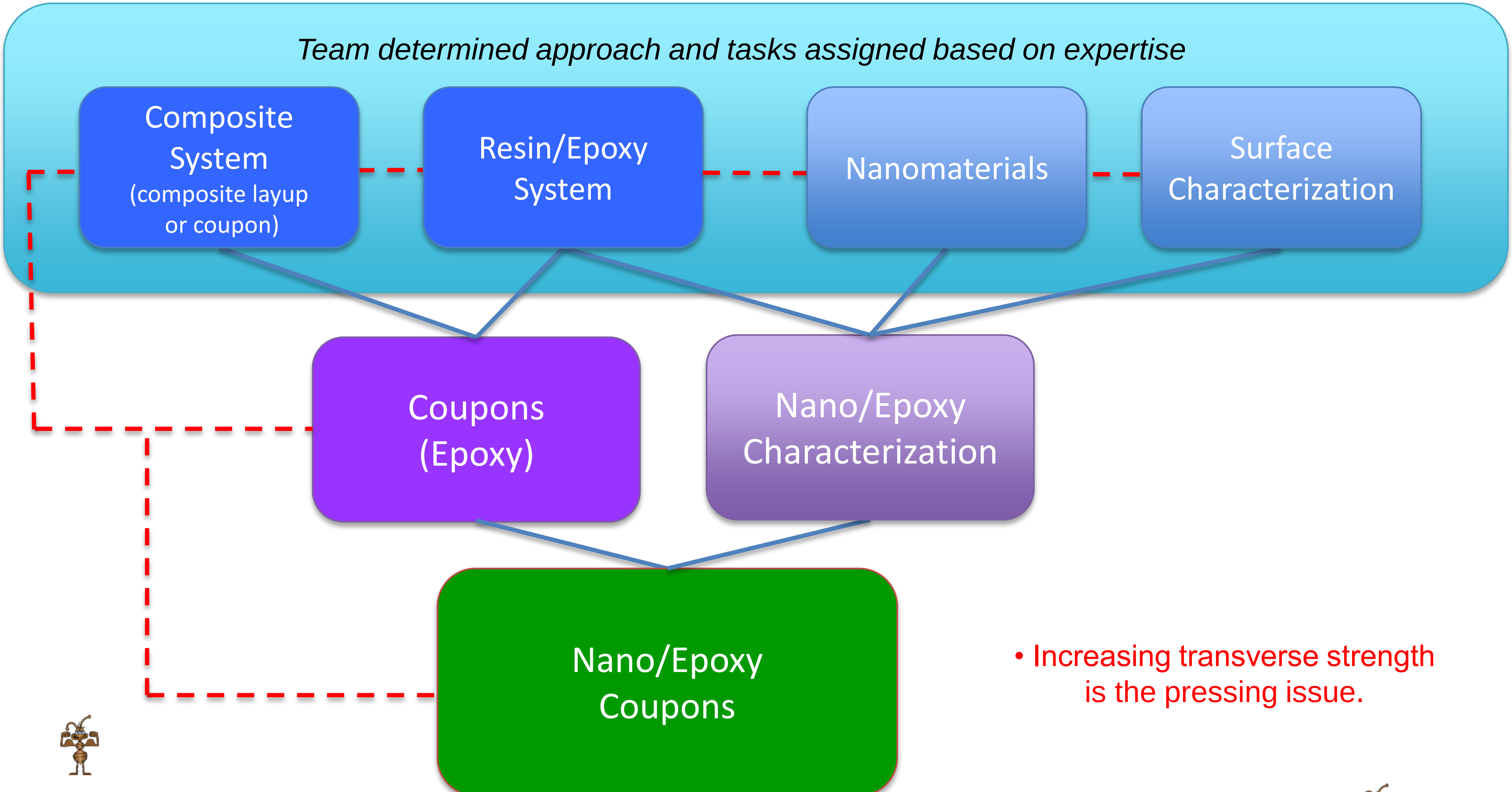
Polym Res (2008)
hem (2006)
t al J. App Polym Sci
olym Sci B: Polymer
em Mater (2010)

Small % changes in the flywheel spin speed leads to magnified energy storage

16,000 rpm → *20,000 rpm*
25 kWh → *39 kWh*
of extractable energy

25 kWh/100 kW per unit = 21 kg TNT

Overall Objectives: Approach based on defining ‘state-of-the-art’ system and elucidating nanoparticle filler effects



- Increasing transverse strength is the pressing issue.

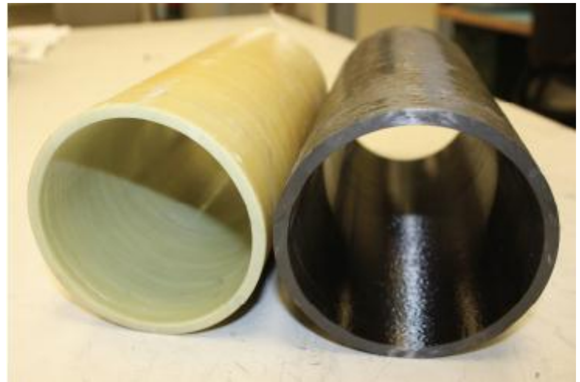
- Incorporation of suggested nanomaterials and/or resins will represent verification of our approach

Test ‘coupons’ reveal a good model system in-place:

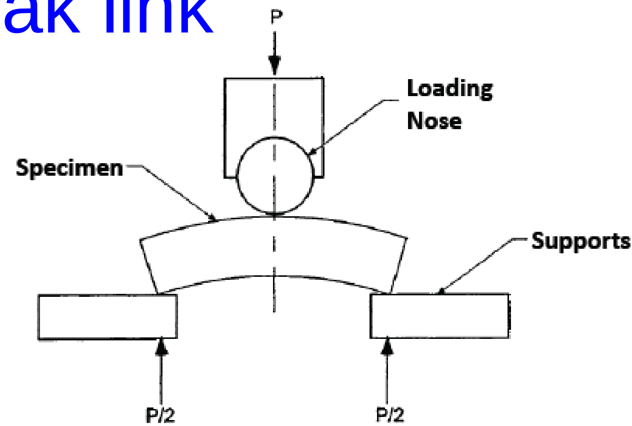
C-fiber/matrix interface weak link

3 components of rim:

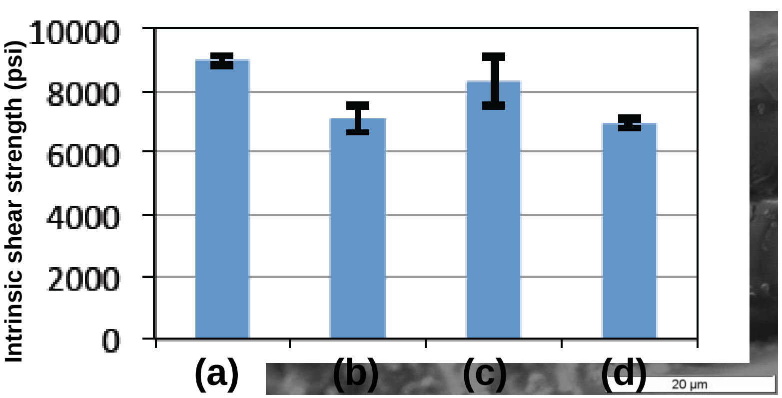
i. carbon-fiber,
ii. glass fiber,
iii. Resin
   (a) **Standard**
   (b) **Epoxy anhydride**
   (c) **Epoxy anhydride + catalyst**
   (d) **Epoxy amine**



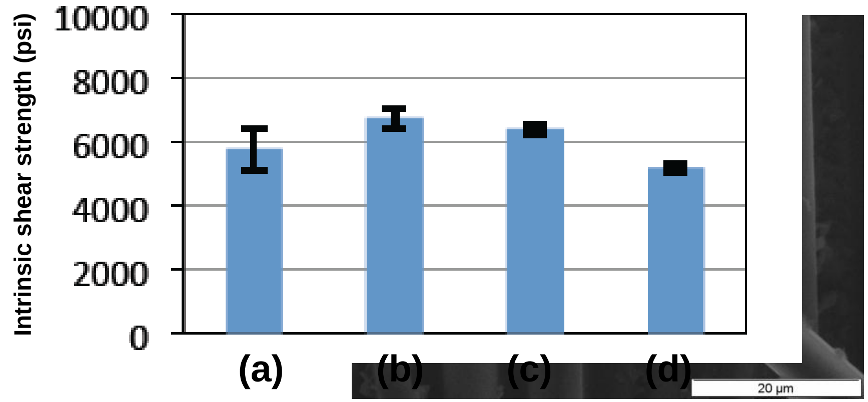
Filament hoop wound glass- and carbon-fiber tubes*



Glass Fiber Test



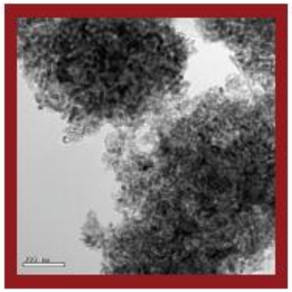
Carbon Fiber Test

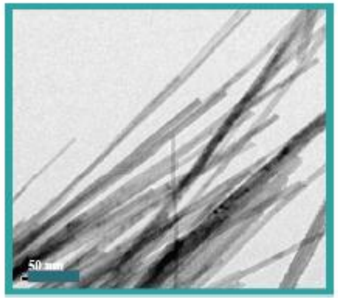


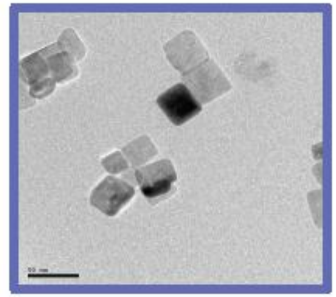
Anhydride resin systems do not show much variation

*special thanks to AFRL

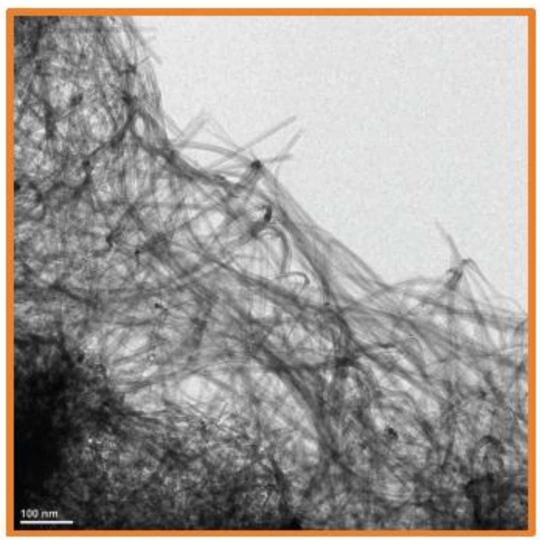
TiO_2 HYBR-synthesized nanofiller selected based on high aspect ratio and large scale production capabilities







hybrid



Surface Modification in volatile solvent (acetone)

↓

Dispersion of Solids in chosen phase (resin, hardener)

↓

Hi Shear Mixing with second phase

↓

Degassing

↓

Casting or Processing

(i) Sarwar et al. *J. Sol-Gel Sci Tech*. (**2007**) 44, 4.

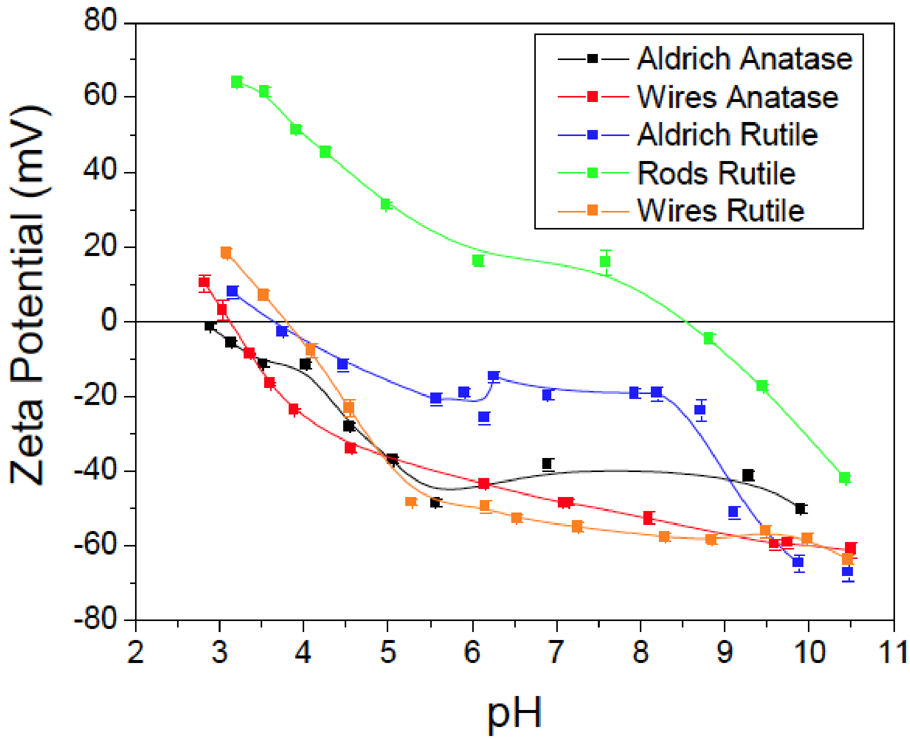
(ii) Adler-Abramovich et al. Angewandte Chemie (**2010**) 49, 1-5.

(iii) Kane et al. J Appl. Cryst. (**2009**) 42, 925.

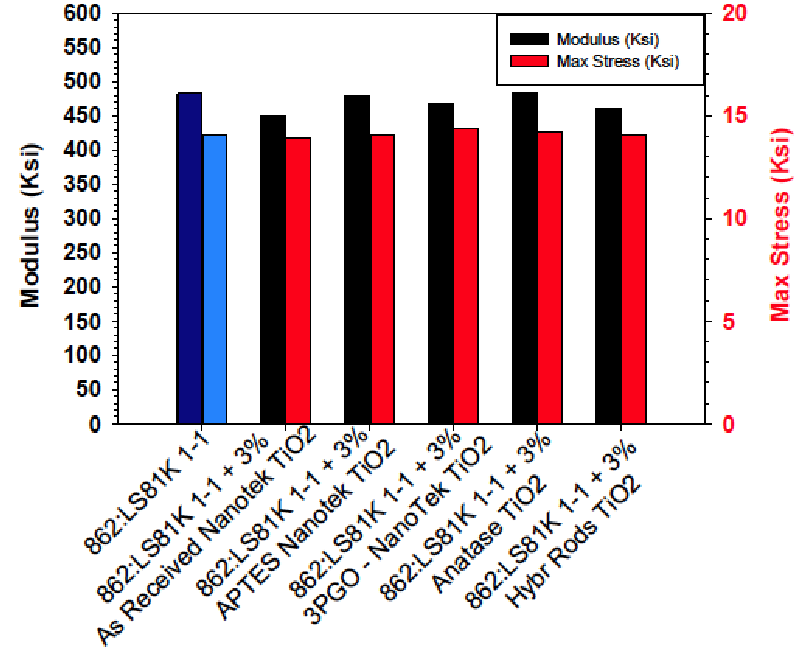
(iv) Sumfleth et al *Polymer* (**2008**) 49, 5105.

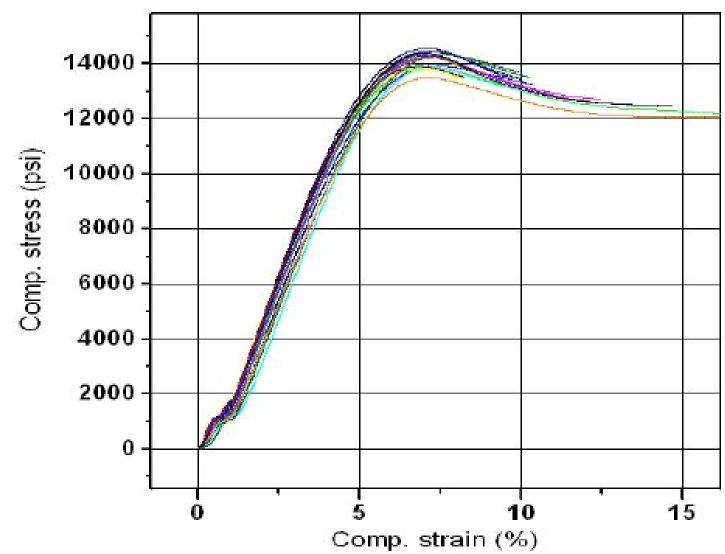
(v) Sangermano et al. Macromol. Mater. Eng. (**2006**) 291 517.

Matrix mechanical properties controlled by intrinsic resin properties: unfunctionalized TiO_2 nanomaterials have little impact

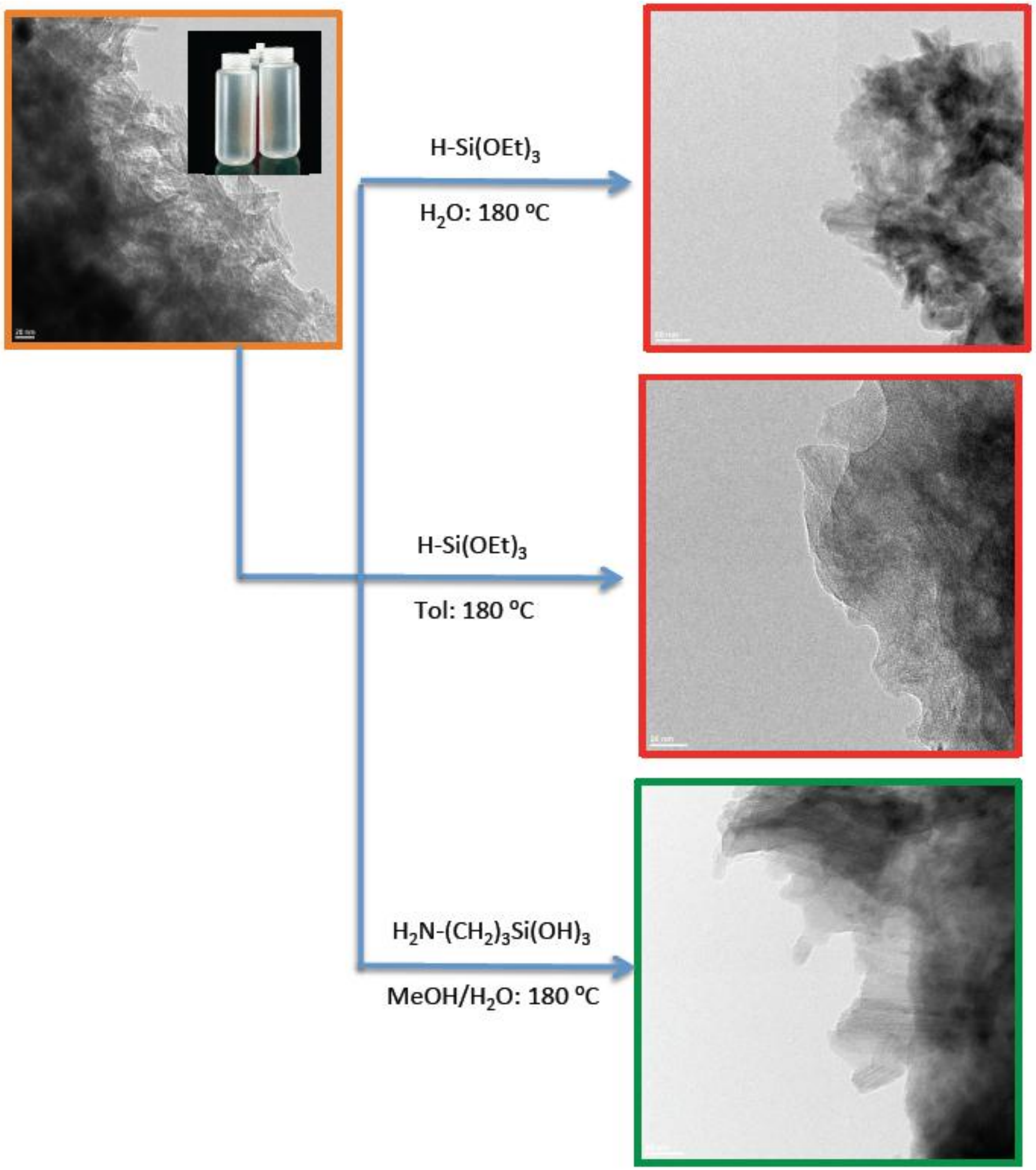


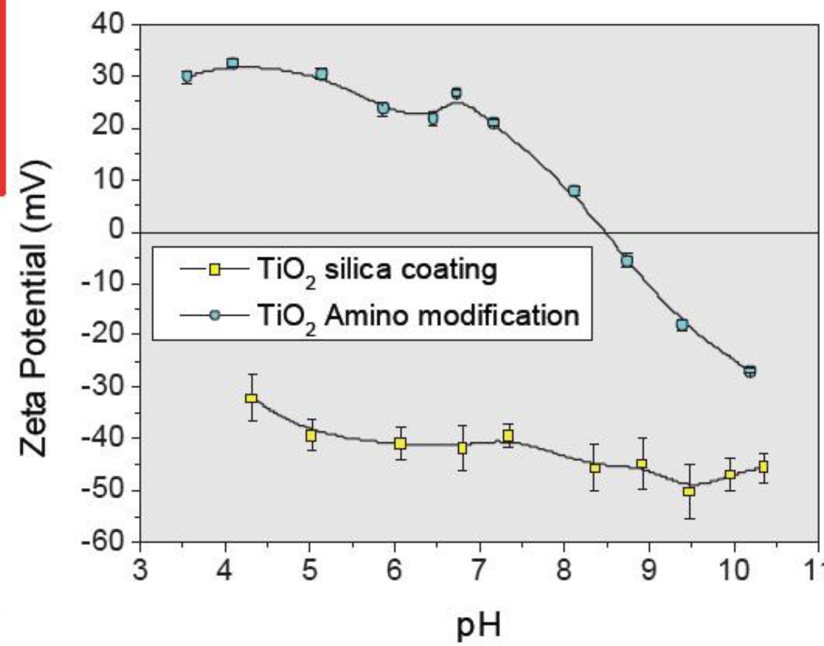
ζ-potential used as diagnostic tool for detecting/determining changes on surface of nanomaterials





Tailored surface chemistry of TiO_2 nanomaterials demonstrated by ζ-potential measurements.





Varied surface modification leads to vast changes in surface charging properties and ζ-potential.

Summary

Nanomaterials:

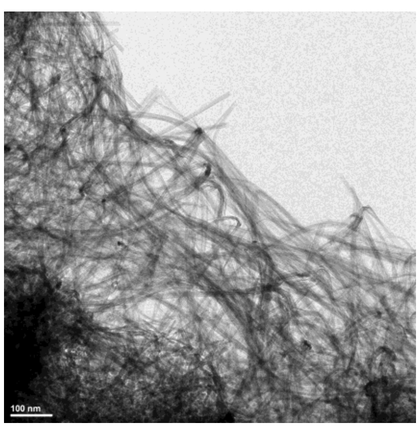
- Generated high aspect ratio TiO_2 nanomaterials on the large scale: HYBR route,
- Varied functionalized nanoparticles successfully generated (ζ-potential),

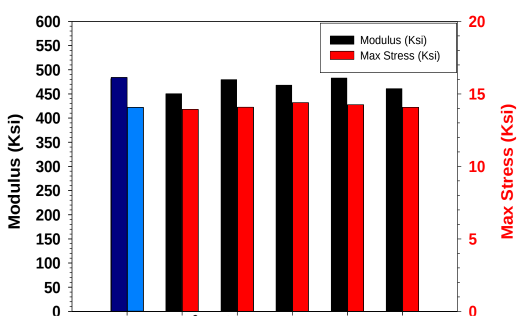
Nanomaterials/Resin:

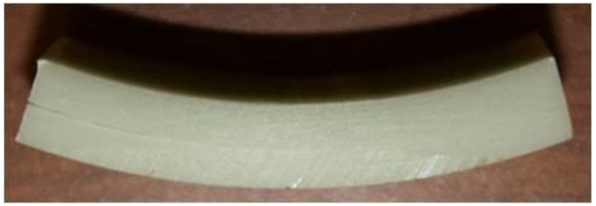
- 'naked' nanoparticles at low loadings have little effect on solid resin matrix's compression behavior.

Coupons:

- System produced that is in agreement with real world effort (High Quality Model system!).
- Test of glass- and carbon-fiber in variety of resin matrices.
- The coupons generated, indicate carbon-fiber is weak link.







Aims (FY11/FY12) for Improved Flywheel Materials

- Synthesize large quantities of high quality nanomaterials
  - + naked
  - + functionalized
  - **+ alternative shapes/compositions/mixtures**

- nanoceramic materials characterization.
  - + ζ–potential measurements
  - **+ Dispersibility in resin systems**
  - **+ stability measurement to improve dispersion.**

- Determine general setup with resin variations.
  - + SEM of fractured composites
  - + interlaminar strength
  - **+ Nanomaterial incorporation changes**

- **Functionalization of components**
  - **+ carbon fiber**
    - **- organic**
    - **- inorganic**
  - **+ nanomaterials**
  - **+ shape**

Dissemination of results has led to many contacts (esp. from last ESS meeting) - not necessarily flywheel researchers

Matt Lazarewicz
VP & CTO
Beacon Power

Prathib Skandakumaran
Innovation Manager
Bayer MaterialScience

Michael R. Strommen, Ph.D.
Renewable Energy Storage Program

Andrew Dobrot,
Senior Consultant
DA2 Consulting

Hopper Energy Systems
Steve Dorozenski

Papers:

(iv) Bell and Boyle "Nanoparticle stabilization mechanisms in epoxy curative fluids: wetting interaction and Van Oss model parameters" (*in prep* for J. Materials Chemistry)

(iii) Celina *et al*. "Cure reactions of advanced composite resins explored by high temperature micro ATR-IR" 241st ACS National Meeting, Anaheim, CA. Program Area: POLY: Division of Polymer Chemistry Symposium (POLY002) Polymers for Energy Storage and Delivery

(ii) Boyle, Steele, Velasquez "Synthesis, Characterization, and Comparison of Family of Sodium Aryloxide Solvated Compounds with their Congener Members" (submitted to Inorganic Chemistry)

(i) Boyle, Steele, Saad "Structural Characterization of a Novel Family of Cesium Aryloxide" (*in Press* - Inorganic Chemistry).

Patents/Technical Advances: None

Presentations: Numerous National Meetings